


Mini-Warriors

Microelectromechanical Systems:
A Munitions Revolution

Dan Jean, Ph.D. ■ Dan Pines ■ Kevin Cochran





In 1959, renowned physicist Dr. Richard Feynman proposed the idea of very tiny machines that could perform micro-level tasks with macro-level effects. Today such machines exist, measuring only millimeters, with gears and levers smaller than dust mites. In smart phones, they change display orientations as you move the phone, and in cars, they collect speed, acceleration and steering data, sending that data to an in-vehicle network.

These “microelectromechanical systems,” or MEMS, are increasingly found in systems we use daily, replacing larger, heavier, and less reliable components at lower costs. They are freeing up space in systems, enabling performance improvements and added functions, and they are performing previously unimaginable tasks at the micro level. Like their significant transformation of commercial systems, MEMS have the potential to transform munitions across defense systems, as found in MEMS development at the Naval Surface Warfare Center Indian Head Explosive Ordnance Disposal Technology Division (Indian Head EODTD).

Revolution in Commercial Products

“MEMS promises to revolutionize every product category,” wrote manufacturing expert Dr. Xuan F. Zha of the National Institute of Standards and Technology. That revolution was indicated by the integration of the first commercially made MEMS sensor into automotive airbags in 1993. Measuring less than 1 cm², this MEMS detected crashes and activated air bags, replacing sensors that were orders of magnitude larger.

MEMS, which vary in design and function, are produced by a process associated with making integrated circuits. Using micromachining, materials are deposited, molded and etched on silicon, which is harder than most metals and has semiconductor properties. The result is a micro system, with tiny moving parts and microelectronic circuits that sense and act.

The benefits of MEMS have been increasingly recognized. Not only are they smaller and lighter than the devices they replace, but they are cheaper because the cost of manufacturing and materials is smaller. At just \$5 apiece, the first commercial MEMS reduced air-bag systems’ costs from roughly \$500 to \$100. It also proved highly reliable. A decade later, the maker of that MEMS accelerometer had sold more than 100 million units for air bags and other systems, reporting “less than one failure per billion hours of operation.”

The integration of MEMS devices for other uses also increased system functionality. In less than a decade, the BMW 740i had more than 70 MEMS devices, enabling anti-lock

Jean and **Cochran** are mechanical engineers and **Pines** is a materials scientist in the Fuze and Initiation Systems Branch at the Naval Surface Warfare Center Indian Head Explosive Ordnance Disposal Technology Division.

braking, active suspension, appliance and navigation control, vibration monitoring, fuel sensing, noise reduction, rollover detection, seat-belt restraint and tensioning and more.

MEMS' debut in the automotive industry led to varied uses in other systems. By 2011, an estimated 3 billion MEMS were used to heat and apply ink in inkjet printers. Incorporated into cameras, these tiny machines stabilize optics and enable clear photos, even when held by unsteady hands. If you have played Nintendo Wii, a MEMS in the hand-held controller senses and transmits body movements to the video game—much like the Lycra suit with 85 MEMS, worn by actors, which aided computer-generated imagery in the movie “Iron Man 2.”

In the biotech industry, MEMS have aided micro-level tasks. They sense blood pressure, monitor glaucoma-related eye pressure and pump insulin when needed. Additionally, researchers have developed MEMS that provide a high degree of control over stimuli that cells receive in lab environments.


According to a Yole Development report, *Status of the MEMS Industry 2013*, the MEMS market will double between 2012 and 2018, expanding from \$11 billion to \$22 billion. That expansion undoubtedly will include increased use of MEMS in munitions.

The Promise for Munitions

In movies, the term “explosives expert” often describes someone with competence in this area. To some degree, that characterizes the Division at Indian Head. The Division does more, however. It researches and develops explosives, propellants and pyrotechnics, a field called “energetics” because the materials release chemical energy. The explosive cartridges activating car air bags are traceable to those in ejection seats, developed at Indian Head. The Division also develops counters to energetic threats, such as improvised explosive devices. Because of this work, the Division serves as a Department of Defense (DoD) Energetics Center.

Shortly after MEMS' introduction into the marketplace, the Division began investigating them for munitions. It did what MIT Professor Judy Hoyt advocated: “To innovate in products, one has to understand the processes by which these products are made.” The Division set up a clean room to characterize and fabricate MEMS. While many such clean rooms exist, the one at Indian Head EODTD is the only one certified to handle and integrate explosives with MEMS, including firing small amounts in a test chamber.

The Division's investigation led to developing MEMS for possible use in underwater, sea surface, land and air-delivered munitions. It first characterized commercial MEMS for the torpedo U.S. Navy surface ships will use to kill enemy torpedoes. Within this 6.75-inch-diameter, anti-torpedo torpedo, eight MEMS sensors aid navigation by measuring acceleration, angular rate and flow, thus enabling detonation at a safe distance from the launching ship.



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The Division also developed MEMS fuzes. Fuzes have been called the brains of munitions. They keep a munition safe, arm it after firing and then detonate it at an opportune time relative to a target. How fuzes do this varies. Some are mechanical, detonating on impact. Some use timers, and some rely on a tiny radar to detect targets and then detonate. All are relatively big, however. For example, a torpedo fuze is about the size of a coffee can. Fuzes also take up a fair portion of a munition's weight. In the 10-pound, 81mm mortar round, the fuze weighs a half-pound.

The MEMS fuzes produced by Indian Head EODTD are about fingernail size, with mechanical and electronic features only a tenth of a hair's width. The first was for the anti-torpedo torpedo. Although it uses a macro-size fuze, significantly reduced in size by the Division, its experimental MEMS fuze informed development of such fuzes for more widely used munitions.

These MEMS fuzes work at the micro-level, interfacing with munitions at the macro-level, as exemplified by one developed for mortars. After launch, a “G” sensor measures acceleration and, when a given number of Gs is reached, removes a safety lock in the MEMS, the first step toward arming. Another sensor measures the round's spin rate and, at a set number, signals removal of a second lock, arming and readying the munition for a fire signal. This may come from a point-detonating switch, a delayed detonation setting, or another sensor detecting a target. The signal initiates a tiny explosive in MEMS' first unlocked section, setting off another explosive in the second unlocked section, which detonates the main explosive.

These MEMS fuzes do something else: harvest energy. They convert launch acceleration into electricity. Thus, MEMS fuzes can power not only their electronics but additional MEMS sensors. They can be power sources in munitions, which previously lacked them, thus allowing incorporation of additional functions. Energy-harvesting MEMS are also cheaper, safer, faster-activating and longer-lasting power sources than batteries.

MEMS fuzes also free up space in existing munitions. This extra space can be used for improved capabilities and additional functions.



MEMS clean room at Naval Surface Warfare Center Indian Head Explosive Ordnance Disposal Technology Division, the only one certified to handle and integrate explosives with MEMS.

Improved Capabilities. More room in munitions allows addition of more propellant, thus increasing range, which U.S. forces in Afghanistan needed for mortars and shoulder-launched munitions. Another option would be to add more explosive, thus increasing lethality. For example, the 81mm mortar round carries about a pound of explosive. Replacing its present, half-pound fuze with the dime-size MEMS could increase the explosive payload by almost 50 percent.

Additional Functions. MEMS fuzes and added sensors and technologies may provide the following new functions:

- *More fuzing functions.* For example, today's 40mm grenades detonate only on impact. However, MEMS fuzes could delay detonation until after impact. More sensors could be added, such as those with radar or radio frequency (RF) capabilities, making it possible to detect targets and detonate in close proximity.
- *Faster arming.* Warfighters need this for shoulder-launched munitions in close engagements. Their time between firing and impact is about a fifth of a second. That means fuzes must arm munitions in less time, which MEMS fuzes can.
- *Precision guidance.* These technologies are getting smaller and cheaper, making them increasingly available. A guidance system with a MEMS fuze soon will be demonstrated in 81mm and 120mm mortars, and could be incorporated similarly into the 2.75-inch-diameter Hydra rockets launched by helicopters, fixed-wing aircraft and possibly Navy surface ships.

MEMS fuzes also can endure tough environments. Electronics in fuzes for medium-caliber munitions, such as 30mm,

experience severe shock and vibration in gun barrels, with acceleration exceeding 60,000 Gs. Also, munitions for hard targets must have fuzes that function after penetration, which has been problematic. MEMS fuzes have sustained 100,000 Gs and high-velocity impacts on hard targets, making them suitable for missiles, artillery, naval gunfire rounds and future railgun projectiles. MEMS sensors already are in the Extended Range Guided Munition, Hellfire missile and Small Diameter Bomb.

Additionally, MEMS make new munitions possible. MEMS fuzes and sensors, along with advances in explosives and propellants, can lead to smaller, lighter and more powerful munitions, which is the trend in warfare. Such munitions are sought for U.S. ground warfighters, who carried more than 130 pounds each in Afghanistan. Attack aircraft have gone from carrying 2,000-pound bombs to the 250-pound Small Diameter Bomb, allowing more targets to be hit per sortie, and smaller munitions would enable even more. Furthermore, smaller and lighter munitions especially are needed for ever-smaller unmanned systems.

Just as MEMS do incredibly small tasks like manipulating cells in medical research, they can do the incredibly small tasks with respect to munitions and even micro-vehicles. Fuzes could further shrink for nano-energetics—nanometer-size explosive and propellant particles—releasing energy faster and enabling very powerful and very tiny munitions. MEMS also may be used in micro-thrusters for miniature munitions or aerial micro-vehicles. An autonomous, 4-by-7-millimeter micro-robot, using nano-energetics integrated with microchips, already has been demonstrated.

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MEMS uses even go beyond detonating munitions. They could help reduce traumatic brain injuries, which more than 150,000 U.S. military personnel have suffered since 2000. Most of these injuries are caused by blasts, but newly developed MEMS sensors, which can be worn in warfighters' helmets, will detect the blast pressures that cause brain injuries. Such quick detection will alert medical personnel in time to arrest brain cell death with serums and other treatments.

Compelling Reasons: Reliability and Low Cost

"Munitions system reliability must be addressed soon, otherwise a critical aspect of our warfighting capability will be jeopardized and held to even higher levels of scrutiny," stated a 2005 Defense Science Board report, *Munitions System Reliability*. It also stated, "Fuzes based on integrated circuits, Micro-Electro-Mechanical Systems and integrated fuzing, targeting and guidance systems can provide greater reliability."

On 1,400 identified sites alone, "Estimated clean-up cost of current unexploded ordnance is tens of billions of dollars," according to a 2003 Defense Science Board report. Of great concern is unexploded ordnance from cluster munitions in the battlespace. These constitute the vast majority of U.S. indirect tactical fires. Some manufacturers claim submunition failure rates of 2 percent to 5 percent, while mine clearance specialists report 10 percent to 30 percent failure rates, according to a Congressional Research Service report. In 2008, DoD policy mandated that U.S. forces after 2018 will employ only cluster munitions "that do not result in more than 1 percent unexploded ordnance (UXO)," further stating, "The 1 percent UXO limit will not be waived."

MEMS fuzes have long been seen as capable of reducing failure rates. "MEMS devices offer the opportunity for 5x to 10x greater reliability, performance, and service life through improved safe-arming/detonating functions and inherent quality,

which is currently lacking in smaller bomblet and submunition ordnance," stated a 1995 DoD assessment, *Microelectromechanical Systems Opportunities*.


MEMS also can aid reliability by helping monitor munitions' health. Ordnance is designed for a life averaging 5 to 8 years, but it is often stockpiled for about 25 years. Over time, ordnance reliability can be affected by chemical changes, accelerated by extreme temperature and poor handling. Making matters worse, it is hard to tell whether it is still good. In Operation Iraqi Freedom, one of eight Patriot missile containers was dropped, causing concern that propellant grains or guidance components may have been damaged. Yet, the dropped container could not be identified as it had no visible damage. Thus, all eight were sent to the United States for evaluation and possible repair—costing \$22 million.

In a demonstration in Germany and Indiana and aboard Navy ships, MEMS that could sense such drops were incorporated into munitions packages. Their data and other data were collected via RF tags by a system that monitored the health of munitions. A similar idea was recommended by the Defense Science Board's *Munitions System Reliability* report. In the future, such systems conceivably could communicate with MEMS inside munitions, assessing fuzes and other health aspects.

In a time of austere defense budgets, there is another compelling reason for munitions-related MEMS: low costs. After MEMS commercial debut, the DoD report *Microelectromechanical Systems Opportunities* assessed these devices for their potential cost savings: "A \$30,000 missile typically contains \$1,000 worth of conventional accelerometers and gyroscopes. An equivalent MEMS device, costing \$20, can be directly substituted in this platform. This represents a 50x subsystem cost reduction." Just as a \$10 MEMS blood pressure monitor replaced a \$600 macro-size one in the medical community, MEMS can provide similar savings in munitions across defense systems.

Looking Ahead

Industry provides a model for MEMS implementation. "We are seeing a massive proliferation of MEMS devices across a broad range of applications: from mobile handsets, tablets and pico projectors, to health/medical monitors, automotive safety systems, the smart grid, gaming, and robotics," said Karen Lightman, managing director of the MEMS Industry Group.

That proliferation should occur in defense. MEMS devices, particularly fuzes, can help add functions and reliability to munitions and other defense systems at low costs. In doing so, they can help maintain technological advantage for U.S. warfighting in a time of tight budgets and growing challenges. Especially now, defense needs the MEMS revolution that's happening throughout commercial industry. 

The authors can be contacted at daniel.jean@navy.mil, kevin.r.cochran@navy.mil, and daniel.pines@navy.mil.